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published in
Journal of Tropical Ecology
1997

DOI (link to publisher)
10.1017/S0266467400010609

document version
Publisher's PDF, also known as Version of record

Journal of Tropical Ecology (1997) 13:427–447. With 3 figures

Chemistry of bulk precipitation in southwestern Viti Levu, Fiji

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ABSTRACT. The amounts and chemical composition of bulk precipitation were investigated over a continuous 21-mo period (January 1990 to September 1991) at four sites along an East–West transect perpendicular to the coast of Southwest Viti Levu, Fiji. Measured rainfall totals in 1990 ranged from 1796 mm at the coastal Korokula station to 2113 mm at the inland Tulasewa station, which is somewhat higher than the long-term average of 1707 mm at a reference weather station located in the centre of the study area. The first 9 mo of 1991 were relatively dry (range 1027–1533 mm) with a total of 1157 mm at the reference site as compared to a long-term average of 1330 mm. Concentrations of all investigated constituents in bulk rainfall were low, except during the passage of cyclone Sina due to the deposition of large amounts of, especially, chloride, sodium and sulphate in sea spray. Concentrations of sodium and magnesium could be explained fully by maritime contributions to the rainfall composition at all sites. Maritime contributions to the concentrations of calcium, sulphate and potassium accounted for 10–40% of the total, whereas bicarbonate, ammonium, nitrate, silicon, aluminium, iron and manganese were derived exclusively from terrestrial sources. The annual atmospheric nutrient deposition rates were low by pan-tropical standards, particularly when the contribution of cyclone Sina was excluded. Annual totals (in kg ha^{-1}) ranged from 2.4–8.8 for nitrogen, 0.4–1.1 for phosphorus, 2.3–4.9 for potassium, 1.4–1.9 for calcium and from 1.1–1.3 for magnesium. The inclusion of the contribution by the cyclone more than doubled the deposition of potassium, calcium and magnesium, although values still remained well within the range reported for humid tropical areas. The estimated atmospheric deposition of nutrients over a typical rotation period (16 y) was sufficient to balance losses in harvested *Pinus caribaea* logs (stemwood plus bark) of potassium, calcium and magnesium, but not of nitrogen and, probably, phosphorus. Nutrient losses associated with the harvesting of stemwood alone were compensated entirely by the atmospheric inputs.

KEYWORDS: atmospheric deposition; Fiji; nutrient budget; *Pinus caribaea*; plantation forestry; rainfall chemistry; South-west Pacific; sustainability of site fertility; tropical cyclones.

INTRODUCTION

The atmospheric deposition of nutrients generally forms an important contribution to the nutrient cycle of forest ecosystems in humid tropical regions, where soils are often of low fertility (Vitousek & Sanford 1986). This is all the more true for plantation forests of fast-growing tree species, such as *Pinus*

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caribaea, which are usually grown in relatively short rotations (15–20 y). The periodic removal of nutrients in harvested forest products (notably stemwood and bark) and the associated nutrient losses due to soil disturbance and enhanced leaching (Bruijnzeel 1990) may lead to a gradual depletion of soil nutrient reserves when such losses are not balanced by a combination of atmospheric nutrient depositions and inputs from the weathering of soil minerals (Bruijnzeel & Wiersum 1985, Hase & Fölster 1983). In this context, studies of the chemistry of rainfall are required as a first step to assess whether short-rotation plantation forestry is sustainable from a nutrient point of view.

Reliable data on the chemistry of precipitation or atmospheric nutrient inputs for tropical regions have become increasingly available during the last decades (Andreae *et al.* 1990, Asbury *et al.* 1994, Bruijnzeel 1989, Burghouts 1993, Dugan & Ekern 1984, Galloway *et al.* 1982, Gunadi 1993, Hase & Fölster 1983, Hendry *et al.* 1984, Lesack & Melack 1991, Lewis 1981, Nye 1961, Parker 1985, Turvey 1974). However, vast parts of the humid tropics have remained uncovered. One such region is the South Pacific Ocean where the only available study focused on the effects of marine sea-salts on the acidity of rainfall in Samoa (Pszenny *et al.* 1982), rather than on atmospheric nutrient deposition. The present study is therefore the first to provide estimates of the rate of atmospheric nutrient deposition for a centrally located island in this part of the world (Viti Levu, Fiji), which has yet escaped large-scale industrialization and its associated environmental problems.

Two processes of nutrient deposition are generally recognised, i.e. wet and dry deposition (Whitehead & Feth 1964). The usual practice is to integrate the two by collecting bulk samples of rainfall, although recently some attempts have been made to quantify inputs via wet and dry deposition separately under humid tropical conditions (Lesack & Melack 1991, Stoorvogel 1993).

The temporal and spatial variability of rainfall in the tropics is generally high (Riehl 1979). Furthermore, the chemical composition of rainfall at a particular site does not depend only on amounts and seasonal distribution of rainfall (Lesack & Mellack 1991), but also on wind speed and direction (Weijers & Vugts 1990a) as well as on the location of the site with respect to potential sources of atmospheric nutrients. These sources can be divided in background sources (such as the ocean) and more periodic, local sources, such as erupting volcanoes (Dugan & Ekern 1984, Gunadi 1993, Scholl & Ingebritsen 1995, Veneklaas 1990), wildfires (Clayton 1976) and industrial or agricultural emissions (Weijers & Vugts 1990b). Deposition of nutrients arising from background sources may be quantified fairly accurately by relatively short studies (1–3 y), as long as the rainfall patterns during the study period are not too dissimilar from the long-term average. However, periodic inputs require a much longer time series to establish their effect on long-term nutrient deposition.

The present study was carried out in the southwestern part of Viti Levu, the largest island of the Fiji group, as part of a more extensive study of the water

and nutrient dynamics of *Pinus caribaea* plantation forests on former grassland soils (Waterloo 1994). Amounts and chemical composition of rainfall were measured at four sites along an east–west transect extending 1.5–15 km from the coast (Figure 1) to study the spatial distribution of rainfall and the corresponding inputs of nutrients with increasing distance from the ocean.

Like many other tropical regions away from the equator (Manton & Bonell 1993), Fiji is affected by cyclones and the sea spray deposited during such extreme events is likely to constitute another important source of solutes in rainfall. Because the precipitation chemistry of tropical hurricanes has hardly been studied, the effects of the passage of cyclones Rae and Sina in March and November 1990 on the atmospheric nutrient inputs will be discussed in some detail.

STUDY SITES

Location

The location of the rainfall stations and the Nabou weather station of the Fiji Meteorological Service are shown in Figure 1. The Korokula station (site 1; 17°59′S, 177°17′E) formed the western end of the transect at 35 m a.s.l., about 1.5 km from the coast. Koromani station (site 2; 18°00′S, 177°18′E) was situated at *c.* about 2 km from the ocean at a slightly higher elevation (90 m a.s.l). Oleolega station (site 3; 18°00′S, 177°21′E) was located at 112 m a.s.l. at a distance of *c.* 6 km from the ocean. The transect ended in the east at Tulasewa station (site 4; 18°00′S, 177°27′E), which was located some 15 km inland at an elevation of 116 m a.s.l. The first two sampling stations were on grassy knolls at appropriate distances (*c.* 50 m) from pine stands, whereas the third and fourth stations were within large grassy areas surrounded by pine plantations. From 1973 onwards daily rainfall totals have been collected by the Fiji Meteorological Service at the Nabou weather station (17°57′S, 177°21′E, 30 m a.s.l.), which lies roughly in between sites 2 (Koromani) and 3 (Oleolega) (Figure 1).

Climate

The climate of Viti Levu is seasonal maritime tropical and is strongly influenced by the presence of several north–south stretching mountain ranges (900–1400 m a.s.l.) dividing the island in a humid (rainfall >3000 mm y^{-1}) climate at the windward, eastern side and a dry (rainfall <2000 mm y^{-1}) climate at the leeward, western side (Krishna 1980). The present study was conducted in the dry zone and the following summary of the climate is mainly based on data provided for Nadi Airport (17°45′S, 177°27′E, 16 m a.s.l.) and the weather station at Nabou (Basher 1986a, Reddy 1989a). The long-term average annual rainfall for Nadi Airport (1942–1985) amounts to 1867 mm (range 864–2983 mm), whereas that for Nabou (1974–1995) is somewhat lower at 1707 mm (range 826–2498 mm). Rainfall at Nabou shows a distinct seasonal pattern with

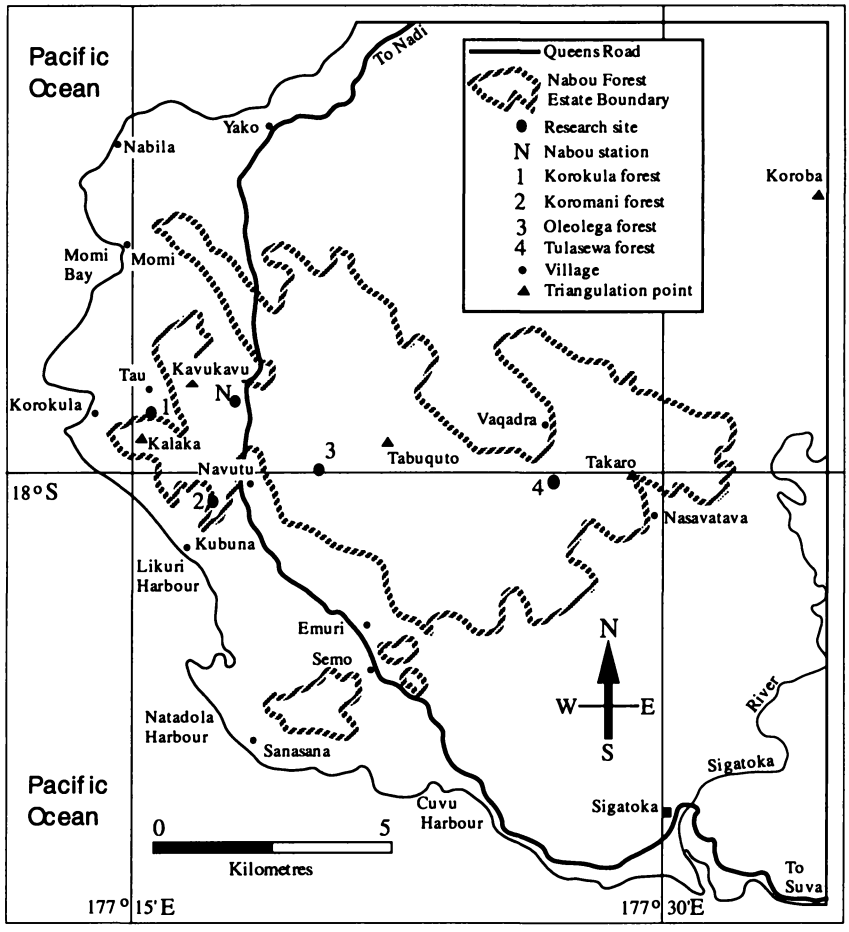

Figure 1. Location of the Korokula (site 1), Koromani (site 2) Oleolega (site 3) and Tulasewa (site 4) sampling stations within the Nabou Forest Estate, Viti Levu, Fiji, together with that of the Nabou weather station maintained by the Fiji Meteorological Service.

low average monthly totals (<100 mm) between May and October, and high values (up to 300 mm) between November and April (*cf.* Figure 3). Convection is the dominant rainfall generating process during the wet season, with most storms occurring between 13:00 h and 18:00 h, whereas rainfall in the dry season is more often associated with the passage of low pressure troughs, leading to a more equal distribution of the rain (Waterloo 1994). Although 'cloud stripping' may provide an additional source of moisture to the rain forest areas in the humid highland zone of Viti Levu, this is not the case in the lowlands of southwestern Viti Levu where the occurrence of fog, other than the occasional early-morning ground fog, is extremely rare (Gabites 1979).

The predominant winds are east to southeasterly trade winds, which blow throughout the year but are most pronounced during the dry season. Wind

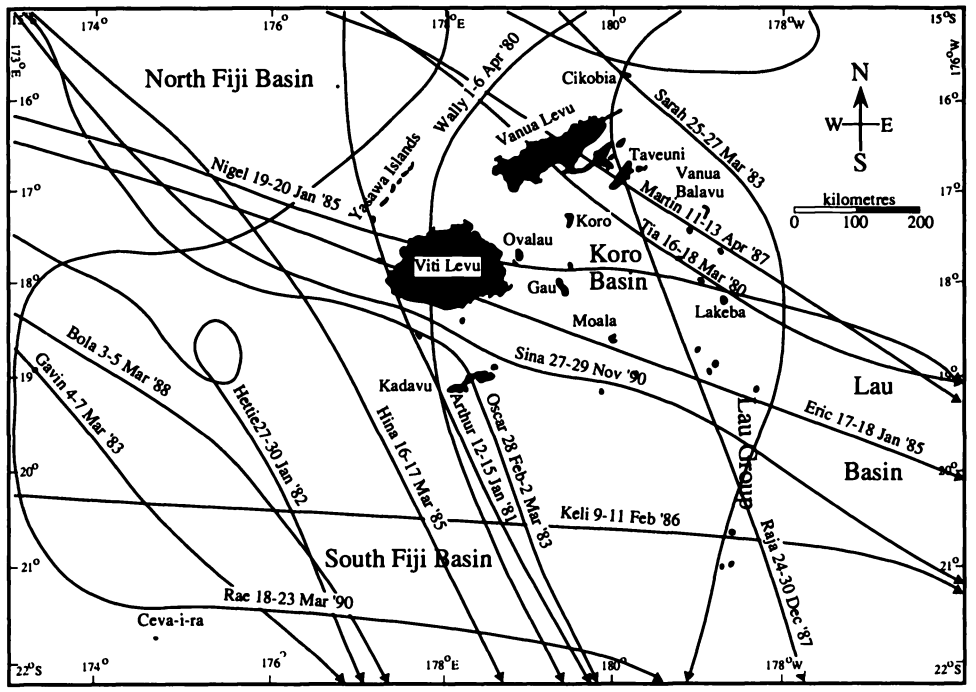

Figure 2. Paths of tropical cyclones that have affected the Fiji group over the period January 1980–December 1991 (Source: Fiji Meteorological Service).

speeds are generally low with an average value of 2.8 ± 0.4 m s^{-1} at Nadi Airport. Wind speeds are slightly higher during the dry season than during the wet season, with a maximum monthly average of 3.4 ± 1.4 m s^{-1} in October *vs.* a minimum value of 2.4 ± 1.0 m s^{-1} in April (Reddy 1989b). Tropical cyclones usually develop above the Pacific Ocean to the West or Northwest of Fiji during the southern summer (November–May), which then move southeastwards with the upper tropospheric winds (Figure 2). The Fiji group experiences an average frequency of one cyclone every 1.3 y. From 1970 until 1991, 15 cyclones with sustained wind speeds exceeding 17 m s^{-1} (gale force or more) affected Viti Levu (Basher 1986b). Six of these have caused substantial damage to the forests in Southwest Viti Levu. During the study period (January 1990–September 1991) two cyclones (Rae and Sina) passed, one of which (Sina) caused major damage.

METHODS

Rainfall sampling procedures

Three totalizing rainfall gauges and a rainfall recorder (SIAP UM-8100) were installed at each sampling site in such a way that there was no obstruction above an angle of 30° whilst the surrounding grass was kept short. A standard

rainfall gauge (Lambrecht) with an orifice of 100 cm^2 and a capacity of 150 mm was used as a reference for the other gauges. A second collector (orifice 100 cm^2, capacity 400 mm) provided information at times when rainfall amounts exceeded 150 mm. The two gauges were emptied at intervals ranging from a few days to a week and on each occasion the electrical conductivity (EC) of the collected rain water was determined with a portable EC meter developed by the Vrije Universiteit Amsterdam. A separate rain gauge was used to collect samples for chemical analysis. It consisted of a plastic funnel (orifice 471 cm^2) placed on top of a white PVC cylinder at a height of 0.7 m. The funnel drained into a second container of chemically inert plastic placed inside the PVC cylinder. This provided low light conditions within the container, thereby diminishing biological activity and increasing the stability of ammonium and phosphate concentrations (Ridder *et al.* 1985). Contamination by insects or organic debris was prevented by a chemically inert 2 mm wire mesh on top of the funnel (coarse material) and a piece of chemically inert filter wool in the funnel outlet (fine material). Bulk samples for chemical analyses were collected at monthly intervals during dry weather, and more frequently during wet periods. Samples were always collected shortly after large rain storms to include any salt and dust particles deposited earlier on the gauges during dry periods. The funnels and containers were thoroughly cleaned with fresh rain water and the filter wool was replaced after each sampling occasion.

Water for cation analysis, silicon and phosphate was collected in clean 100 ml polyethylene bottles after filtering through a 0.45 μm Millipore filter. For conservation purposes 0.7 ml of 65% nitric acid suprapur was added to the bottle before sampling to obtain a final sample pH of about one. Water for anion analysis, total nitrogen, total phosphorus and laboratory measurements of the EC and pH was collected in clean 200–ml polyethylene bottles. All samples were stored in the dark at 4 °C until transport by air to the Netherlands for analysis.

Chemical analytical procedures

The EC and pH were determined in the field, during or shortly after sampling. The pH was measured with a combined electrode (INGOLD) connected to a pH-meter (Metrohm AG). All samples were analyzed at the laboratory of the Faculty of Earth Sciences of the Vrije Universiteit Amsterdam. The EC was remeasured with a Phillips digital conductivity meter (Model PW-9526). The pH was remeasured with a digital pH-meter connected to a combined electrode (Orion Research). The pH-meter was calibrated against buffer solutions (Baker Chemical Co.) with pH values at 25 °C of 4.00 and 7.00. Sodium and potassium were determined by flame photometry using an Eppendorf flame photometer. Aluminium, calcium, total iron, magnesium, manganese and silicon were determined on a Perkin-Elmer Inductively Coupled Plasma (ICP) emission spectrophotometer. Chloride, sulphate, nitrate, phosphate and

Table 1. Maximum absolute analytical errors in the determination of nutrient concentrations (mg l^{-1}) in water samples (T. Baër, *pers. comm.*).

Solute	Error	Solute	Error	Solute	Error	Solute	Error
Na	0.40	NH_4	0.03	Cl	0.40	Total Fe	0.04
K	0.10	Al	0.04	SO_4	0.60	Total N	0.02
Ca	0.24	Mn	0.04	NO_3	0.20	Total P	0.02
Mg	0.20	Si	0.40	PO_4	0.02		

ammonium were determined by spectrophotometry on Technicon and Skalar Auto-analyzers. Chloride was determined with the ferricyanide method of Zall *et al.* (1956), sulphate was determined with the methylthymol-blue method of Greenberg *et al.* (1980), nitrate by cadmium reduction (Hendrikson & Selmer-Olsen 1970), phosphate by ascorbic acid reduction (Black *et al.* 1965) and ammonium with the modified Berthelot reaction using salicylate and dichloro-isocyanurate (Krom 1980). Total phosphorus was determined on the ICP using the molybdiphosphoric acid method of Boltz & Mellon (1948). Total nitrogen was determined as ammonium on the ICP after destruction (Kjeldahl digest). The analytical accuracy for each nutrient was usually smaller than 2% of the concentration of that nutrient in the highest standard solution (Table 1).

Nutrient losses in harvested timber

Nutrient losses in harvested timber were determined for the 16-y-old *Pinus caribaea* forest at Oleolega (site 3). The logs (stemwood plus bark) were weighed at the TROPIK Wood Industries Ltd. weighing bridge. Field-moist weights of 12 sample trees were converted to oven-dry values (70 °C) by drying three subsamples per stem (taken at the top, centre and base) until constant weight. Concentrations of nitrogen, phosphorus, potassium, calcium, magnesium, boron, manganese and zinc were determined at the Forest Research Institute New Zealand (see Waterloo (1994) for details).

RESULTS AND DISCUSSION

Rainfall amounts and characteristics

To obtain a realistic value for the long-term annual atmospheric nutrient deposition, rainfall and other meteorological conditions during the study period should be close to their long-term averages (Lesack & Mellack 1991). In Southwest Viti Levu, variations in temperature, relative humidity, wind speeds (excluding cyclone events) and irradiance are fairly small between years, unlike those in rainfall (range 826–2498 mm y^{-1} at Nabou between 1974–1995, Waterloo 1994). The effect of any deviations of the former from their long-term averages on annual atmospheric nutrient deposition was therefore assumed negligible compared to the influence exerted by differences in rainfall between years. The monthly rainfall pattern recorded at Oleolega (site 3) during the study period and the long-term pattern for Nabou are given in Figure 3.

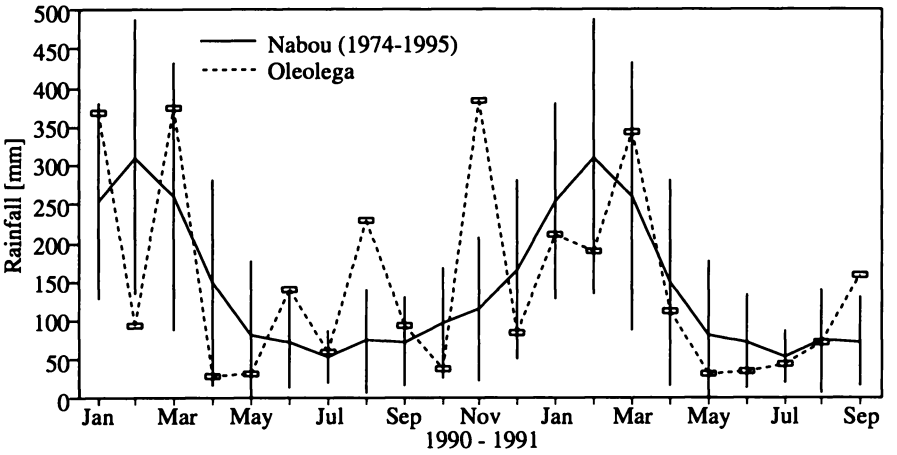

Figure 3. Monthly rainfall totals at site 3 (Oleolega) over the period January 1990–September 1991 plus long-term values for Nabou weather station (1974–1995); vertical bars represent standard deviations from the mean. Source of Nabou data: Fiji Meteorological Service.

Monthly rainfall totals during the study period were generally within one standard deviation from the mean and rainfall during the study may therefore be considered to be reasonably representative of long-term conditions, particularly in view of the large spatial variation in rainfall in the area (Krishna 1980). The high rainfall amounts recorded for March 1990 (observed range at the four study sites: 374–469 mm; long-term average at Nabou: 260 ± 174 mm) and November 1990 (observed range: 219–438 mm; long-term average at Nabou: 115 ± 92 mm) were associated with the passage of cyclones Rae and Sina, respectively.

Cyclone Rae formed about 400 km Southwest of Fiji on 18 March 1990 and reached its peak intensity on 23 March, when it was located 225 km south of Kadavu (Figure 2). As such the cyclone posed no direct threat to any inhabited island of Fiji, but the group experienced moderately strong winds with a maximum hourly average of 16 m s^{-1} and maximum gusts of 25 m s^{-1} (Prasad 1990). The magnitude of the maximum wind gusts indicated that the force of cyclone Rae had a return period of about 2 y (Basher 1985). The cyclone was accompanied by torrential rains on 20–23 March. A total of 249 mm of rainfall was recorded over 4 d in Nabou forest. The highest rainfall (443 mm) was recorded at Monasavu in the interior of Viti Levu (Prasad 1990). Cyclone Sina originated some 1000 km Southwest of Viti Levu on 25 November 1990, and passed the western and southeastern parts of the Fiji Islands in the night of 27–28 November at a speed of 17 km h^{-1}. High wind speeds occurred during the passage of the cyclone with a maximum hourly average of 38 m s^{-1} measured in the early morning of 28 November (4:00 h) on a hill top near Koromani forest (site 2; *cf.* Figure 1). The wind direction was northeast in the period preceding the cyclone and changed to northwest during the 3-h period of passing Koromani forest. The maximum gust was estimated at 84 m s^{-1}, indicating a return period

Table 2. Seasonal and annual rainfall (mm) at the four study sites and Nabou station, Fiji, during the study period. Corresponding long-term averages (1974–1995) for Nabou are given for comparison. W = wet season; D = dry season.

Season	Sites				Nabou	Nabou* (1974–1995)
	1	2	3	4		
1990 W	1184	1309	1330	1554	1003	1254
1990 D	612	595	620	559	520	453
1990	1796	1904	1950	2113	1523	1707
1991 W	721	736	856	1183	822	975
1991 D	306	320	343	351	335	355
1991	1027	1156	1199	1533	1157	1330

*Source: Fiji Meteorological Service, Nadi

of 10 y (Basher 1985). Most rainfall occurred in the 48 h preceding the cyclone, whereas relatively little was recorded during the actual passage.

Rainfall totals at the respective study sites during the wet (November–April) and dry (May–October) seasons of 1990 and part of 1991 (January–September) are given in Table 2, along with the corresponding annual totals and the long-term averages for Nabou. An increase in rainfall with distance from the coast is evident during the wet season, but not during the dry season. This may be explained by the fact that wet season rainfall is mainly convective, whereas dry season rainfall is more frequently associated with the passing of low-pressure troughs through the area (Waterloo 1994).

Chemical composition of bulk precipitation

The concentrations of solutes in bulk rainfall were low, particularly those of phosphate, total phosphorus, silicon, aluminium, iron and manganese, which were often below their respective detection limits. Table 3 shows the weighted average concentrations of respective constituents during the wet and dry seasons for all sites, as well as the average ion concentrations in seawater at Natadola Harbour as sampled on 9 December 1990 and 19 July 1991. Whenever concentrations fell below the detection limit, the latter value was used in the calculations. The fact that actual average concentrations for such constituents will be somewhat lower is indicated by the 'smaller than' signs in Table 3. The maximum absolute analytical errors (Table 1) suggest that errors in measured concentrations above the detection limit could be as large as 200%. However, actual errors are thought to be much smaller because of the consistency in the concentrations as observed for the different sites. Furthermore, deviations in the ionic balances of the weighted averages (Table 3) were less than 10%, with the exception of that for dry season rainfall at Tulasewa which had a deviation of −13%. Standard deviations from the means are not presented here, but ranged generally between 10 and 40%, with maximum values of around 70% from the means for dry season total nitrogen and ammonium concentrations at site 3 (Oleolega), and wet season nitrate at site 1 (Korokula).

Table 3. Weighted average nutrient concentrations (mg l^{-1}) in rainfall at the four study sites for wet season (W) months, dry season (D) months, during cyclone Sina (excluding site 4), and in seawater at Natadola Harbour. n = sample size; EC represents the electrical conductivity in µS cm^{-1} at 25 °C.

	Site 1			Site 2			Site 3			Site 4		Natadola
	W	D	Sina	W	D	Sina	W	D	Sina	W	D	Seawater
n	12	10	1	12	11	1	12	11	1	18	11	2
EC	7.3	10.2	130	7.7	10.3	166	6	10.2	131	6.4	7.7	60,850
pH	5.46	5.17	5.15	5.34	5.22	5.43	5.45	5.40	4.83	5.60	5.17	8.34
Na	0.70	1.09	21.23	0.73	1.13	27.32	0.52	0.80	21.30	0.57	0.73	10,820
K	<0.14	<0.14	0.66	<0.11	<0.14	1.62	<0.10	<0.24	1.09	<0.22	<0.25	408
Mg	<0.07	<0.07	2.66	<0.06	<0.07	3.42	<0.07	<0.06	2.63	<0.06	<0.07	1,356
Ca	<0.09	<0.10	0.82	<0.08	<0.09	1.07	<0.10	<0.09	0.86	<0.09	<0.09	392
NH_4	0.29	0.47	<0.05	0.22	0.25	0.07	0.23	<0.40	0.16	0.29	<0.19	0.26
NO_3	<0.27	<0.15	<0.05	<0.10	<0.12	0.11	<0.13	<0.19	0.15	<0.15	<0.15	0.05
N-Tot	0.64	0.34	<0.02	0.31	0.37	<0.02	<0.11	<0.23	0.23	0.11	0.14	0.16
Cl	1.32	2.12	38.55	1.43	1.91	50.08	1.08	1.51	38.35	1.08	1.56	20,210
HCO_3	1.13	0.96	<0.05	0.75	1.22	<0.05	0.84	1.56	<0.05	0.88	<1.17	140
SO_4	<0.79	<0.61	5.79	<0.79	<0.90	8.07	<0.79	<1.06	5.04	<0.57	<0.52	2,754
PO_4	<0.02	<0.02	<0.02	<0.02	<0.03	<0.02	<0.02	<0.02	<0.02	<0.02	<0.03	0.39
P-Tot	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.03	<0.02	<0.02	<0.03	0.16
Si	<0.05	<0.05	<0.05	<0.05	<0.08	<0.05	<0.11	<0.06	<0.05	<0.05	<0.05	0.1
Al	<0.05	<0.05	0.05	<0.05	<0.05	0.05	<0.06	<0.05	<0.05	<0.05	<0.05	0.02
Fe	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.05	<0.05	<0.05	<0.05	<0.02	0.02
Mn	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.05	<0.02	<0.02	<0.02	0.02

The concentrations in bulk rainfall showed a distinct seasonal trend with low concentrations during the wet season and somewhat higher concentrations during the dry season (Table 3). This presumably reflects the degree of dilution of dry deposition in the gauge, because of the longer intervals between storms and lower rainfall intensities during the dry season (Waterloo 1994).

The contribution of cations in wet and dry season rainfall (on an equivalent basis) decreased in the order: sodium > ammonium > potassium > magnesium > calcium, whereas that of anions decreased in the order: chloride > bicarbonate > sulphate > nitrate > phosphate. Hence ammonium and bicarbonate were much more prominent in rain water than in seawater which showed a decrease in the order: sodium > magnesium > potassium > calcium > ammonium for cations, and in the order: chloride > sulphate > bicarbonate > phosphate > nitrate for anions.

Rainfall chemistry during cyclones

The chemistry of rainfall associated with cyclone events has not been studied before in the South Pacific. As indicated earlier, two cyclone events of different magnitude occurred during the present study, which provided an opportunity to determine the impact of such events on overall atmospheric deposition. Solute concentrations in rainfall during cyclone Rae (March 1990) did not differ from overall wet season concentrations for cyclone-free periods and the cyclone rainfall data were therefore pooled with the remaining wet season samples. However, ion concentrations in the rainfall associated with cyclone Sina (November 1990), the centre of which passed at less than 50 km west of the study area, were much higher than those observed during cyclone-free periods. The data collected during cyclone Sina at sites 1-3 have therefore been presented separately in Table 3. No information was obtained for site 4 where the rainfall collector had been blown away during the cyclone. Rainfall collected after cyclone Sina passed showed high concentrations of such typically 'maritime' ions as sodium, magnesium, chloride and sulphate, but not for the more 'terrestrial' ions (*e.g.* ammonium, nitrate, bicarbonate). Furthermore, the sequence of ion concentrations on an equivalent base in the rainfall during the cyclone was similar to that of seawater, suggesting considerable deposition of sea spray at the height of the cyclone.

Solute sources

Salt particles may be considered to be the dominant form of dry deposition in the largely forested study area. They originate during the breaking of waves when fine droplets of seawater are ejected into the atmosphere. After evaporation of the water, the residual salt may be transported upwards by wind and act as condensation nuclei in clouds (Drever 1982). Fractionation is not important during the process. Therefore, the major ions (sodium, potassium, calcium, magnesium, chloride, sulphate) are present in precipitation in more or less the same proportions as in seawater (Duce & Hoffman 1976). This implies that

rainfall on small, isolated oceanic islands, where other sources of pollutants are absent, may essentially be considered as very dilute seawater (Galloway *et al.* 1982).

To what extent ions in rain water are derived from the ocean or from terrestrial sources may be evaluated by comparing the observed chemical composition of the rain with that predicted on the basis of the assumption that the ocean is the only source. Only marginal amounts of chloride are added by terrestrial sources in a non-volcanic and non-industrial area such as Southwest Viti Levu. If fractionation during the forming of salt particles at the sea-air interface is neglected, oceanic contributions to the concentrations of ions other than chloride in bulk rainfall ($[X_p]$) can be calculated from their proportion with respect to the concentration of chloride in sea water ($[Cl_s]$) and in bulk rainfall ($[Cl_p]$) (Eriksson 1960) according to Equation 1.

$$[X_p] = \frac{[X_s] \cdot [Cl_p]}{[Cl_s]} \quad (1)$$

The composition of sea water along the coast of Southwest Viti Levu was taken as the average of two samples collected in Natadola Harbour (Table 3). Concentrations in bulk rainfall in excess of those calculated from equation (1) given above may be attributed to terrestrial sources (Eriksson 1960). It is convenient to express the oceanic contribution as the ratio (in percent) of the calculated to the measured concentrations in rainfall. The results are given in Table 4 for wet and dry season rainfall, as well as for the rainfall associated with cyclone Sina.

The concentrations of sodium and magnesium in both bulk rainfall and cyclone rainfall at the respective sites may be fully attributed to the ocean because their ratios all exceed 90%, indicating that any terrestrial influence is next to negligible. The concentrations of ammonium and bicarbonate, on the other hand, must reflect terrestrial sources as their ratios are close to zero. The intermediate ratios obtained for potassium, calcium and sulphate suggest both oceanic and terrestrial sources. The difference between the wet and dry season

Table 4. The oceanic contribution (in %) to the measured composition of wet and dry season bulk rainfall and during the passage of cyclone Sina, at four sites on Fiji.

	Site 1			Site 2			Site 3			Site 4	
	W	D	Sina	W	D	Sina	W	D	Sina	W	D
Na	101	105	97	105	91	98	110	101	96	102	115
K	19	31	118	27	28	63	22	13	71	10	12
Mg	136	203	97	156	186	98	100	165	98	129	154
Ca	28	43	92	36	43	91	20	33	86	23	34
NH_4	0	0	0	0	0	1	0	0	0	0	0
Cl	100	100	100	100	100	100	100	100	100	100	100
HCO_3	1	2	0	1	1	0	1	1	0	1	1
SO_4	23	47	91	25	29	85	19	19	104	26	41

ratios is small, with a possible exception for potassium, calcium and magnesium at the coastal station of Korokula (site 1), suggesting that there is no distinct seasonal pattern in oceanic contributions.

Relatively high ratios for potassium, calcium and sulphate were observed in rainfall collected after the passage of cyclone Sina. This, and the fact that the concentrations of such typically oceanic constituents as sodium, chloride and magnesium were much higher than usual (Table 3), suggests that deposition of sea spray during the cyclone largely determined the chemical composition of the rainfall. Additional support for this contention comes from the fact that concentrations in cyclone rainfall were highest near the coast (sites 1 and 2) and had decreased at the more inland site 3 (Table 3).

Atmospheric deposition of nutrients

The atmospheric deposition of nutrients at each site can be calculated by combining weighted average concentration data (Table 3) with the corresponding amounts of rainfall (Table 2). Because the rainfall pattern in 1990 resembled the long-term pattern (Figure 3), the calculated deposition (excluding that during cyclone Sina) for 1990 may be assumed to give a reasonable estimate of the long-term annual deposition during cyclone-free years. Seasonal and annual amounts of nutrient deposition (excluding cyclone Sina) at the respective sites are given in Table 5, whereas contributions associated with cyclone Sina are given separately in Table 6. Atmospheric deposition was distinctly higher during the wet season, in spite of the higher ion concentrations in dry season bulk precipitation. Differences between sites were fairly small, although the coastal sites received somewhat higher amounts of sodium, chloride and nitrogen than the more inland sites. The trends in sodium and chloride deposition are likely to reflect the distance of the site from the ocean (Weijers & Vugts 1990b), but the reason for the observed decrease in total nitrogen deposition with distance from the coast remains obscure. Most probably, it is related to the burning of sugar cane fields in the vicinity of the coastal stations of Korokula and Koromani (*cf.* Lewis 1981). The impact of the higher rainfall at site 4 (Tulasewa) on the magnitude of the atmospheric deposition is small due to the correspondingly lower ion concentrations.

The annual atmospheric deposition of nutrients during cyclone-free conditions was low by pan-tropical standards. This was particularly true for potassium, calcium, magnesium and total nitrogen, which were at the lower end of the range published by Bruijnzeel (1989) for 13 selected stations in the humid tropics (rainfall range: 1575–8631 mm y^{-1}; Table 6). The atmospheric inputs of phosphorus, potassium and magnesium in the study area were fairly close to those observed at a site in Côte d'Ivoire experiencing similar annual rainfall (1835 mm), but having a less well-developed dry season. The calcium input at the latter site, however, was much higher (6.6 kg ha^{-1}), presumably as a result of significant inputs of Saharan dust during the dry season (Stoorvogel 1993).

Table 5. Seasonal and annual atmospheric nutrient deposition (kg ha^{-1}) at the four study sites on Fiji in 1990. Deposition during cyclone Sina has been excluded. W = wet season, D = dry season.

	Site 1			Site 2			Site 3			Site 4		
	W	D	Total	W	D	Total	W	D	Total	W	D	Total
Na	7.4	6.7	14.0	8.6	6.7	15.3	6.2	5.0	11.2	8.8	4.1	12.9
K	<1.5	<0.8	<2.3	<1.2	<0.8	<2.1	<1.2	<1.5	<2.7	<3.5	<1.4	<4.9
Mg	<0.7	<0.4	<1.1	<0.7	<0.4	<1.1	<0.9	<0.4	<1.2	<0.9	<0.4	<1.3
Ca	<1.0	<0.6	<1.6	<0.9	<0.5	<1.4	<1.2	<0.6	<1.8	<1.4	<0.5	<1.9
NH_4	3.1	2.9	5.9	2.6	1.5	4.1	2.7	<2.5	<5.2	4.4	<1.1	<5.5
NO_3	<2.9	<0.9	<3.8	<1.2	<0.7	<1.9	<1.6	<1.2	<2.8	<2.4	<0.8	<3.2
N-Tot	6.7	2.1	8.8	3.6	2.2	5.8	<1.3	<1.4	<2.7	1.6	0.8	2.4
Cl	14.0	13.0	27.0	16.8	11.4	28.2	12.9	9.3	22.2	16.9	8.7	25.6
HCO_3	11.9	5.8	17.8	8.8	7.2	16.0	10.0	9.6	19.7	13.6	<6.5	<20.1
SO_4	<8.3	<3.7	<12.0	<9.2	<5.4	<14.6	<9.5	<6.5	<16.0	<8.9	<2.9	<11.8
PO_4	<0.2	<0.1	<0.4	<0.2	<0.2	<0.4	<0.9	<0.2	<1.1	<0.3	<0.2	<0.5
P-Tot	<0.2	<0.1	<0.3	<0.2	<0.1	<0.4	<0.3	<0.2	<0.5	<0.2	<0.2	<0.4
Si	<0.5	<0.3	<0.8	<0.7	<0.5	<1.1	<1.3	<0.4	<1.7	<0.8	<0.3	<1.1
Al	<0.5	<0.3	<0.9	<0.3	<0.2	<0.5	<0.8	<0.3	<1.1	<0.8	<0.3	<0.4
Fe	<0.2	<0.1	<0.3	<0.2	<0.2	<0.4	<0.6	<0.2	<0.8	<0.3	<0.1	<0.4
Mn	<0.2	<0.1	<0.3	<0.2	<0.1	<0.3	<0.4	<0.2	<0.6	<0.3	<0.1	<0.4

Table 6. Atmospheric nutrient deposition (kg ha^{-1}) at sites 1–3 during the passage of cyclone Sina and for 1990 as a whole, including the contribution of the cyclone. Ranges observed for cyclone-free conditions in 1990, and those observed for other humid tropical locations (Bruijnzeel 1989) included for comparison.

	Cyclone Sina			1990 including Sina			1990 excluding Sina		Humid tropics	
	Site 1	Site 2	Site 3	Site 1	Site 2	Site 3	Min	Max	Min	Max
Na	27.7	37.2	28.2	41.7	52.5	39.4	11.2	15.3	3.3	158.0
K	0.9	2.2	1.4	<3.2	<4.3	<4.1	2.1	4.9	2.5	18.2
Mg	3.5	4.7	3.5	<4.6	<5.8	<4 .7	1.1	1.3	0.7	19.4
Ca	1.1	1.5	1.1	<2.7	<2.9	<2.9	1.4	1.9	1.4	21.8
NH_4	<0.1	0.1	0.2	<6.0	4.2	<5.4	4.1	5.9	1.2	11.5
NO_3	0.0	0.2	0.2	<3.8	<2.1	<3.0	1.9	3.8	<0.1	6.1
N-Tot	0.0	0.0	0.3	8.8	5.8	<3.0	2.4	8.8	5.0	60.0
Cl	50.2	68.3	50.8	77.2	96.5	73.0	22.2	28.2	2.6	85.0
HCO	0.0	0.0	0.0	17.8	16.0	19.7	16	20.1	—	—
SO_4	7.5	11.0	6.7	<19.5	<25.6	<22.7	11.8	16	3.2	20.5
PO_4	0.0	0.0	0.0	<0.4	<0.4	<1.1	0.4	1.1	0.1	1.2
P-Tot	0.0	0.0	0.0	<0.3	<0.4	<0.5	0.3	0.5	—	—
Si	<0.1	<0.1	<0.1	<0.9	<1.2	<1.8	0.8	1.7	0.5	1.5
Al	0.1	0.0	<0.1	<1.0	<0.5	<1.2	0.5	1.1	—	—
Fe	0.0	0.0	0.0	<0.3	<0.4	<0.8	0.3	0.8	0.1	0.9
Mn	0.0	0.0	0.0	<0.3	<0.3	<0.6	0.3	0.6	0.0	0.7

— , no data available.

The atmospheric deposition of nutrients in the Llanos of Southwest Venezuela (annual rainfall *c.* 1800 mm, with a seasonal distribution closely resembling that of Southwest Viti Levu) was distinctly higher than at the present location (Hase 1981). Hase interpreted his findings as being the combined effect of the widespread forest clearing going on in his study area (fire, dust) and contamination by organic debris. Much higher values were also observed for most of the nutrients deposited at a site in the moist semi-deciduous forest zone in Ghana, despite a comparable annual rainfall of 1850 mm (Nye 1961). These are likely to reflect a combination of the explanations given in relation to the quoted Venezuelan and West African studies as well as the limitations of the analytical facilities available in those early days.

Details on the deposition of nutrients during cyclone Sina are presented in Table 6. Solute deposition during cyclone Sina was negligible at all sites for those constituents having low concentrations in seawater (nitrogen, phosphorus, bicarbonate, silicon, aluminium, iron and manganese), compared with the annual deposition under cyclone-free conditions (the observed range of which is also given in Table 6). In contrast, substantial amounts of potassium and sulphate were deposited during the cyclone (40–100% of the annual totals during cyclone-free periods), whereas loadings of sodium, calcium, magnesium and chloride exceeded the respective annual totals by a factor two to three (Tables 5 and 6). The data did not reveal a clear trend with distance from the coast with depositions at the coastal sites of Korokula and Koromani (sites 1 and 2) being similar to those at the more inland Oleolega site (site 3). As indicated earlier, no data were available for site 4 (Tulasewa) but throughfall data collected there after the cyclone confirmed that the deposition of sodium, potassium, calcium, magnesium, chloride and sulphate during the event had also been much higher than that during cyclone-free conditions, although not as high as at sites 2 or 3 (Waterloo 1994). This suggests that, although the deposition of considerable amounts of sea spray was not restricted to the coastal zone *sensu stricto*, it may have decreased further inland from the present sites.

The inclusion of nutrient depositions during the passage of cyclone Sina in the annual totals of 1990 had a very modest effect on the atmospheric inputs of most non-maritime nutrients (ammonium, nitrate, total nitrogen, bicarbonate, phosphate, total phosphorus, silicon, aluminium, iron and manganese). Whilst the deposition of calcium magnesium and potassium did show a large relative increase, it remained well within the range observed for humid tropical regions (Table 6). The annual depositions of such typically maritime ions as chloride, sulphate and sodium, however, increased to such an extent that these were near, or surpassed, the upper end of the published range for the humid tropics (Table 6).

The atmospheric nutrient deposition rates presented in Tables 5 and 6 pertain to nutrients trapped by funnel rain gauges located in grassland areas or in forest clearings. It is well known, however, that forests, with their greater

exposure to wind and their larger leaf surface per unit area, may be more efficient in trapping airborne particles than a standard rain gauge (Hicks 1976, Mayer & Uhlrich 1974, Miller *et al.* 1976, Parker 1983, Vaughan 1976, White & Turner 1970). A comparison of the fluxes of sulphate in rainfall and throughfall for cyclone-free periods suggested that the actual atmospheric nutrient input to the forest could have been up to 45% higher than those based on the rain gauge sampling during the pre-cyclone period (Waterloo 1994). The difference between the trapping efficiency of the rain gauges and the forest canopy became much more pronounced during the passage of cyclone Sina, when the amount of sulphate trapped by the forest canopy was up to 220% higher than that collected by the rain gauge at Korokula (site 1). No differences in trapping efficiencies could be detected after cyclone Sina, which can be explained by the strongly reduced leaf surface area of the forests (defoliation) after the passage of the cyclone (Waterloo 1994).

Atmospheric nutrient inputs and nutrient losses in harvested timber

Whether wood production in plantation forestry is sustainable depends partly on the balance between atmospheric nutrient inputs and exports of nutrients in harvested timber. In the present case, the deposition of nutrients is likely to be strongly influenced by cyclone frequency, paths and intensity, as these will largely determine where, and how much, sea spray will be deposited on top of the atmospheric nutrient deposition occurring under cyclone-free conditions. Unfortunately, data on the chemical composition of rain water associated with cyclone events other than the present data are lacking. This, combined with the very low concentrations of most nutrients in the rainfall, implies that it is difficult to provide accurate estimates of the atmospheric deposition of nutrients during a typical plantation rotation period (15–20 y) for any location in Fiji. As such, there may be large uncertainties in the estimates presented below, particularly in those for phosphorus because this nutrient remained below the detection limit at all times and will therefore have been overestimated. On the other hand, no adjustments were made to account for differences in trapping efficiency of forest canopy and rain gauges because such differences are likely to show a large, unknown variation in time, depending on the age of the plantation, the amount of foliage, exposure to the wind field, cyclone damage, *etc.* Atmospheric nutrient accession totals were estimated for the period 1975 (date of forest planting at site 3, Oleolega) until 1990 (tree harvesting) using the actual monthly rainfall totals measured at the nearby Nabou station. Dry season concentrations (Table 3) were used whenever monthly rainfall fell below 100 mm (as is typical for dry season conditions). In all other cases wet season concentrations were used. Estimates have been made initially for the five macro-nutrients only. The possible deposition of major elements (potassium, calcium and magnesium) during cyclones was taken into account for those years in which the forests in Southwest Viti Levu suffered major cyclone damage (*i.e.* 1983, 1985 and 1990), by adding the deposition of

nutrients during cyclone Sina at Oleolega to the corresponding annual totals calculated for cyclone-free conditions. The results are presented in Table 7.

Table 7. Atmospheric nutrient accession during a 16-y rotation period (1975–1990) *vs.* nutrient exports in harvested pine stemwood and bark at Oleolega (site 3). All values in kg ha^{-1}.

	N	P	K	Ca	Mg
Atmospheric deposition (1975–1990)	<34.4	<7.2	<37.6	<30.4	<27.3
Export via: harvested logs	44.8	5.3	28.7	23.4	11.2
wood	33.8	4.0	23.4	19.2	8.7
bark	11.0	1.3	5.4	4.2	2.5
Balance	>−10.4	<1.9	<8.9	<7.0	<16.1

The total stem biomass harvested from the Oleolega catchment between December 1990 and July 1991 amounted to 54.6 t ha^{-1} (dry weight), of which 6.6 t ha^{-1} was bark. Such relatively low volumes are common in the area due to the substantial reductions in initial stocking of pine stands over a rotation period as a result of repeated cyclone damage. The associated amounts of macro-nutrients exported in the harvested timber are also given in Table 7, distinguishing between amounts in stemwood and bark (see Waterloo (1994) for details).

The resulting nutrient balance (bottom row in Table 7) suggests that atmospheric inputs of nitrogen, and probably also of phosphorus, over the period of a rotation are not sufficient to compensate the export of these elements in harvested timber if both stemwood and bark are harvested. Stripping the bark from the logs in the field would lead to a decrease in the exports of nitrogen (and phosphorus), that would be sufficient to alter the balance such that a positive value is found for nitrogen, and presumably also for phosphorus. However, additional inputs of nitrogen by biological fixation may be such that no nitrogen shortage is to be expected, even if bark material would not be left on-site (Binkley & Giardina 1997). Estimated atmospheric inputs of calcium, magnesium and potassium were more than sufficient to compensate any losses in harvested produce. As such, phosphorus is likely to be the first element to become limiting, also because any phosphorus released by weathering is likely to become immobilized by complexation with the iron and aluminium compounds present in the ultisols of the area (Clayton 1979, Waterloo 1994). The positive cationic balance found by the present study reflects the modest volumes of timber harvested under Fijian conditions and the equally modest amounts of nutrients immobilized in the stems of *Pinus caribaea*, rather than excessively high atmospheric nutrient inputs. As indicated earlier, these inputs were rather low by tropical standards (Bruijnzeel 1989), even when depositions during tropical cyclones were included (Table 6). Elsewhere in the tropics, Russell (1983) and Bruijnzeel (1984) demonstrated that atmospheric nutrient inputs accounted for

a substantial portion of the annual incorporation of potassium, calcium, and magnesium in the stems of *Pinus caribaea* and *Pinus merkusii*, respectively. Values for phosphorus were much lower, which is in agreement with the present findings. A fuller analysis of the respective gains and losses of nutrients throughout a rotation, including losses due to burning of slash, enhanced leaching and localised surface erosion, has been given by Waterloo (1994).

ACKNOWLEDGEMENTS

We gratefully acknowledge the funding for the present study by the Netherlands Foundation for the Advancement of Tropical Research (WOTRO, grant no. W84-295), Fiji Pine Ltd. (FPL), and the Faculty of Earth Sciences of the Vrije Universiteit Amsterdam (FES-VUA). *Vinaka vaka levu* to Mr. J. Dunn, Dr. J. H. R. Heuch, Mr. J. Baba, Mr. G. Carty and all others at FPL for their cooperation and support. The laboratory staff at the FES-VUA, under supervision of Mrs. Tini Bäer, are thanked for their dedication while analyzing the large number of water samples collected during this study. Mrs. Jean Prince from the Forest Research Institute of New Zealand analyzed the wood samples.

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Accepted 21 October 1996